Transformando a Prática Cirúrgica com Visão Computacional: Desenvolvimentos Recentes e Aplicações Clínicas

Transforming Surgical Practices with Computer Vision: Recent Developments and Clinical Applications

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RESUMO

A visão computacional emergiu como sendo uma tecnologia transformadora com o potencial de melhorar significativamente a segurança, eficiência, precisão e formação na prática cirúrgica. Aproveitando algoritmos avançados e inteligência artificial, as aplicações de visão computacional oferecem uma análise em tempo real sobre informação visual durante os procedimentos cirúrgicos, permitindo o suporte à decisão automatizado, avaliação de desempenho e orientação intraoperatória. Este artigo explora os desenvolvimentos recentes na tecnologia de visão computacional no domínio da cirurgia, com um foco particular na sua aplicação em procedimentos minimamente invasivos. Discute também o estado atual da visão computacional na cirurgia, explorando as suas aplicações práticas. O artigo destaca os desafios que devem ser superados para uma adoção clínica generalizada, enfatizando o papel crucial dos esforços coletivos para enfrentar estes obstáculos. Com um foco equilibrado tanto nos avanços técnicos como nas implicações práticas, este manuscrito fornece uma visão abrangente do papel da visão computacional na cirurgia moderna.

PALAVRAS-CHAVE: Algoritmos; Cirurgia Assistida por Computador; Competência Clínica; Inteligência Artificial; Procedimentos Cirúrgicos Minimamente Invasivos; Treino de Simulação

ABSTRACT

Computer vision has emerged as a transformative technology with the potential to significantly enhance surgical practices' safety, efficiency, precision, and training. By leveraging advanced algorithms and artificial intelligence, computer vision applications offer real-time analysis of visual data during surgical procedures, enabling automated decision support, performance assessment, and intraoperative guidance. This article delves into the recent developments in computer vision technology within the realm of surgery, particularly focusing on its application

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in minimally invasive procedures. It also discusses the current state of computer vision in surgery while exploring its practical applications. The article highlights the challenges that must be overcome for widespread clinical adoption, emphasizing the crucial role of collective efforts in addressing these obstacles. With a balanced focus on both the technical advancements and the practical implications, this manuscript provides a comprehensive overview of the role of computer vision in modern surgery.

KEYWORDS: Algorithms; Artificial Intelligence; Clinical Competence; Minimally Invasive Surgical Procedures; Simulation Training; Surgery, Computer-Assisted

Integrating computer vision (CV) technology into surgical practice represents one of the most promising advancements in modern medicine.[1,2] As minimally invasive surgery becomes increasingly prevalent, the need for precise, real-time analysis of surgical environments has grown. When associated with artificial intelligence (AI), CV offers the ability to process and interpret visual data from surgical procedures,[3] where one minute of surgical video is estimated to contain 25 times the amount of data found in computed tomography imaging.[4] CV provides insights that can significantly augment a surgeon's training and decision-making process, empowering them with a new level of precision and efficiency. For example, by deploying a deep neural network comprising a segmentation model to highlight hepatocystic anatomy, Mascagni *et al*[5] demonstrated that AI-based algorithms can be trained to segment hepatocystic anatomy and assess the critical view of safety criteria in laparoscopic imaging.

Recent CV-assisted surgery developments have found fertile ground in minimally invasive surgery, where visual data captured by fiber optic cameras plays a critical role in guiding procedures. Laplante *et al*[6] developed an AI model capable of identifying safe and dangerous zones of dissection on laparoscopic cholecystectomy surgical videos. Complementary, Golany *et al*[7] tested an AI algorithm to recognize surgical phases of laparoscopic cholecystectomy videos spanning a range of complexities, reporting a mean accuracy for surgical phase recognition of 89%. Focusing on laparoscopic appendectomy, Dayan *et al*[8] executed a retrospective single-center study of 499 consecutive laparoscopic appendectomy videos. The authors demonstrated that AI-based CV analysis could accurately assess complexity grading with high surgeons' agreements (76.9% and 94.4% for low and high complexity grades, respectively).

The recent developments in CV-based surgery can be divided into several areas: surgical workflow analysis, intraoperative decision support, performance assessment, and postoperative quality improvement (Fig. 1). Such applications leverage deep learning algorithms to analyze visual data, enabling surgical phase recognition, tool detection, and anatomical structure identification tasks.

PRACTICAL APPLICATIONS OF COMPUTER VISION IN SURGERY

SURGICAL WORKFLOW ANALYSIS

One of CV most significant contributions to surgery is its ability to analyze and optimize surgical workflows.[9] By recognizing different phases of a procedure, CV systems can: (i) provide real-time feedback on the progress of surgery, (ii) help to streamline operations, (iii) reduce the likelihood of error, and (iv) improve surgical education by shortening the learning curve. For instance, CV-assisted algorithms can now self-learn and classify steps in transanal total mesorectal excision procedures with a reported accuracy of 93.2%.[10] In the case of laparoscopic distal gastrectomy, Yoshida *et al*[11] developed a convolutional neural network (CNN)-based image classifier with an overall accuracy of 89%. Takeuchi *et al*[12] successfully used an AI-centric algorithm to annotate the nine surgical steps in robot-assisted minimally invasive esophagectomy, achieving an overall accuracy of 84%. Still, even for other more complex applications, such as laparoscopic pancreatoduodenectomy[13] or laparoscopic cholecystectomy,[14] AI-assisted overall accuracy stage classification was 89.7% and 92.3%, respectively.

INTRAOPERATIVE DECISION SUPPORT

CV technology has the potential to act as a real-time assistant during surgery, offering decision support that minimizes errors. For example, 97% of laparoscopic bile duct injuries have a visual perceptual illusion as a primary cause,[15] and thus, safe dissection requires a continuous interpretation process of the surgical field.[16] Madani *et al*[17] tested an AI-centric model to identify safe and dangerous zones of dissection, as well as anatomical landmarks during laparoscopic

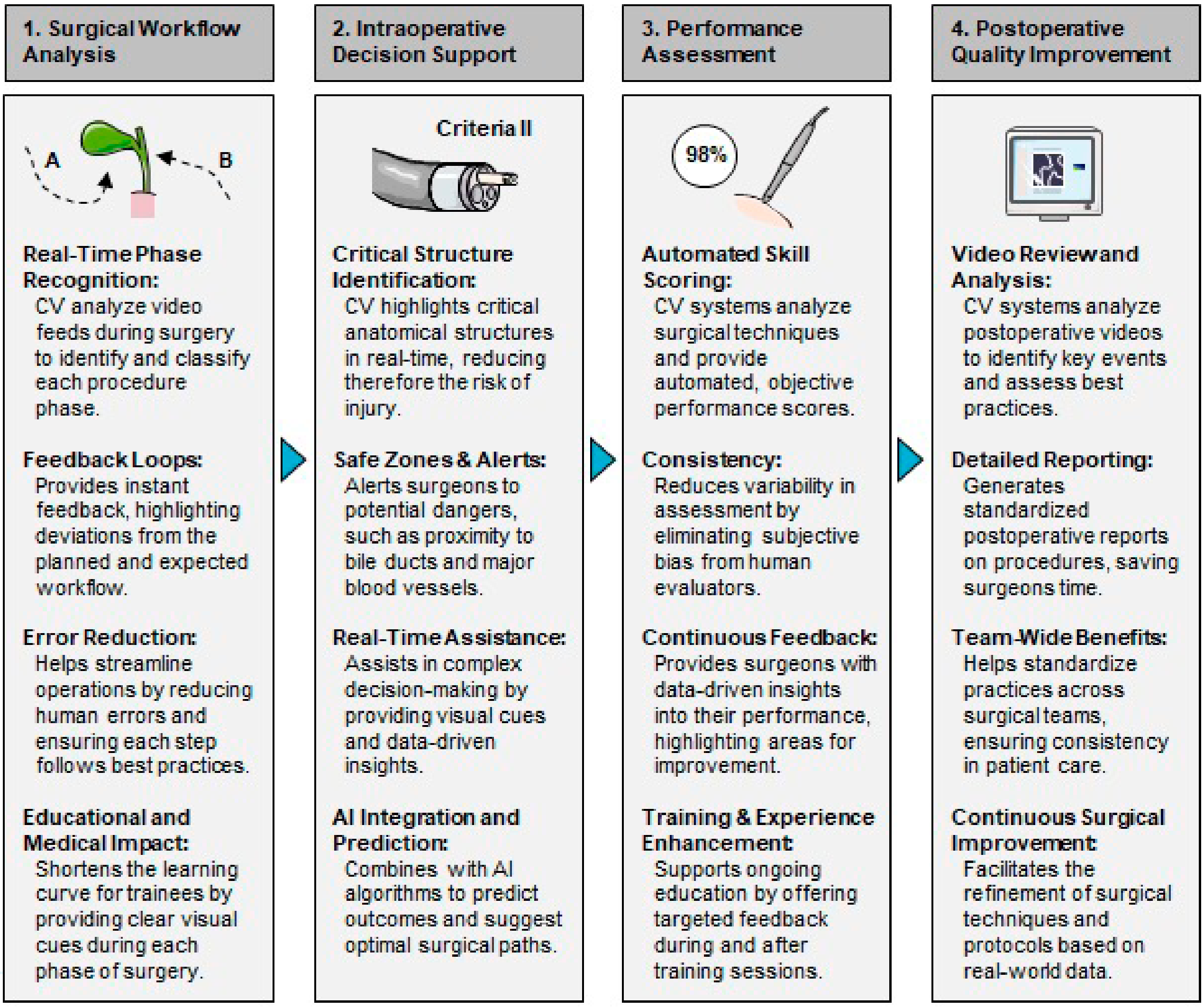

FIGURE 1. Key applications of computer vision in surgery: workflow analysis, decision support, performance assessment, and quality improvement.

cholecystectomy. The authors reported 94% and 83% overall accuracy for safe and not-safe zones, respectively. For the resection of adrenal masses, Sengun *et al*[18] deployed a model that can predict the left adrenal vein anatomy with a dice similarity coefficient of 93%. On the other hand, Nespolo *et al*[19] reported the use of AI-centric CV algorithms for phacoemulsification cataract surgery. The study reported a dice similarity coefficient of 90.23% for pupil segmentation, while 72% of the cataract surgeons involved in the study stated they were most likely to use the platform during complex cataract surgery. In the case of intraoperative hypotension, Wijnberge *et al*[20] executed a single-center preliminary study of patients undergoing elective noncardiac surgery, where using a machine learning-derived early warning system compared with standard care resulted in less intraoperative hypotension. Therefore, by analyzing visual data during a procedure, CV systems can warn about potential risks, such as the proximity of critical structures or the risk of unintended tissue damage.

PERFORMANCE ASSESSMENT AND FEEDBACK

Assessing and improving surgical performance is critical to medical education and ongoing professional development. Traditionally, performance assessment has relied on expert opinion or manual review of surgical videos, which is time-consuming and subject to variability in human judgment.[21] Baghdadi *et al*[22] developed a CV-based system for automated assessment of surgical performance in pelvic lymph node dissections, which outputs a performance score per analysis. To avoid the need for manually collected suturing technical skill scores, Hung *et al*[23] deployed automated suturing technical skill scoring through CV models, using expert and training surgeons' data. Still, in the context of medical suturing training, Yanik *et al*[24] used a 1D residual neural network to classify surgical procedure outcomes and directly predict performance scores after training in Fundamentals of Laparoscopic Surgery. Exploring eye-tracking techniques, which provide a more objective investigation of the visual-cognitive aspects of the decision-making process of training surgeons, Kuo *et al*[25] proposed a deep learning system for laparoscopic surgical skills assessment, correctly classifying skill levels with accuracy between 76.0% and 81.2%. This automated feedback can be particularly valuable in training environments, where trainees can receive immediate, data-driven insights into their performance. Over time, such systems could help standardize surgical training and ensure that all surgeons meet a consistent level of competency before performing procedures independently.

POSTOPERATIVE QUALITY IMPROVEMENT

Beyond intraoperative assistance, CV can also significantly contribute to postoperative quality improvement. By analyzing postoperative surgical videos, CV systems can identify key events and assess whether they were performed according to best practices.[26] Moreover, this information can generate detailed reports highlighting improvement areas at the individual surgeon level and across entire surgical teams. For instance, Derathé *et al*[27] developed a CV-based model to extract postoperatively spatial and procedural annotations of sleeve gastrectomy videos, thus supporting quality procedure assessment and postoperative reporting. Brandenburg *et al*[28] developed a CV-assisted machine learning algorithm for robot-assisted minimally evasive esophagectomy to predict postoperative patient surgical outcomes, contributing to reducing surgeon's annotation efforts and interoperative reporting variability. On the other hand, Loukas *et al*[29] used a CV-driven laparoscopic tasks video annotation for skills assessment and classification, which could recognize the trainees' skill level with an overall accuracy between 71% and 86%. Despite the rapid growth of CV-assisted automated postoperative reporting techniques and their general value for clinical practice, there is a lack of reporting guidelines. Therefore, Meireles *et al*[30] have proposed an established hierarchy for annotating temporal events in surgery, comprising temporal models, actions and tasks, tissue characteristics and general anatomy, and software and data structure. Upon this framework, Filicori *et al*[31] tested the current state-of-the-art commercially available solutions. The team concluded that CV-powered AI analysis is poorly featured in some platforms (step segmentation in 44% of platforms, out-of-body blurring or tool tracking in 33%, kinematic data in 22%, suture time in 11%, and just one platform detailed perfusion imaging), paving thus the way for novel research and technological development.

In conclusion, computer vision is promising to transform surgical practice by enhancing safety, efficiency, and outcomes. Recent developments in CV technology have demonstrated its potential to revolutionize several aspects of surgery, from workflow analysis and intraoperative decision support to performance assessment and postoperative quality improvement. However, realizing CV's full potential in surgery will require overcoming significant challenges related to data quality, ethical considerations, and integration into clinical workflows. As the field continues to evolve, close collaboration between surgeons, AI researchers, and regulatory bodies will be essential to ensure these technologies are developed and implemented to maximize their clinical value while safeguarding patient safety and privacy. The future of surgery is poised to be increasingly driven by data and AI, with computer vision at the forefront of this transformation.

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